Final Technical Report (FTR) Template

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Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

Executive Summary:

The **Advanced Measurement and Analysis of PV Derate Factors** project focuses on improving the accuracy and reducing the uncertainty of PV performance model predictions by addressing a common element of all PV performance models referred to as “derates”. Widespread use of “rules of thumb”, combined with significant uncertainty regarding appropriate values for these factors contribute to uncertainty in projected energy production.

Research activities that are supported by this project include;

1. *Advanced Soiling Study* – determine the influence of soil composition and morphology on attenuation and scattering of light. Develop methodology to reproducibly simulate soiling in a controlled environment.
2. *Improved Modeling of Angle of Incidence Losses* – develops an improved AOI function that accounts for diffuse utilization and soiling (FY13 and 15 only).
3. *Improved Modeling of Solar Spectrum Effects* – Development of a performance model that leverages a low cost spectral sensor. (FY13 and FY14 only)
4. *Methods to Quantify and Predict the Impact of Mismatch Losses on PV Array Performance* – develop and validate methods to estimate string-level performance model coefficients from characterization of individual modules. Develop and validate a method to predict the string mismatch derate factor from available module characterization results

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Task 1: Advanced Soiling Study

Background: Accumulated soil on the surface of a PV module ("soiling") is widely recognized as a significant factor that reduces the power output of PV systems. The California Energy Commission (CEC) estimates annual losses due to soiling to be 7%, while other sources report annual losses ranging from 5 – 25% (Kimber et al., 2006). Factors such as geographic location, rainfall, array orientation and tilt and soil composition contribute to the degree of actual power loss as well as the level of uncertainty system performance predictions. The uncertainties associated with soiling impact the predicted energy yield of installed PV systems and therefore the return on investment. Thevenard and Pelland (2013) have noted that their economic assessments could be improved with a better estimate of soiling losses. The effects of soiling are immediate and influence the value of PV projects during the crucial first few years of operation just as much as in later years after project payback has been achieved.

Slow soil accumulation on photovoltaic (PV) modules presents a challenge to long-term performance prediction and lifetime estimates due to the inherent difficulty in quantifying small changes over an extended period. Most of the available information on the effects of soil has been collected during the operation of installed arrays. Predictive estimates are not typically available for specific sites, so rough estimates are used in long-term models. Thevenard and Pelland (2013) noted that uncertainty in the performance evaluation of large systems is particularly problematic to assessing economic viability. The authors selected a 3% derate factor with 2% uncertainty, but noted that their estimates could be improved with a better understanding of soiling losses. An upper limit to the loss in transmission due to soiling was reported by Elminir et al. (2006). After a certain threshold, the surface is sufficiently saturated to make the effect of additional particulates insignificant. The upper limit observed by Elminir et al. (2006) has been experimentally described by Beattie et al. (2012) as a function of particle stacking. The authors applied sand particles in a narrow size distribution to glass surfaces. They found that particle clustering influences the total obscured area of the slide as an exponential function. This clustering effect is likely responsible for the observation by Mani and Pillai (2010), who note that "dust promotes dust".

Except in the case of extreme weather conditions (Schill et al., 2011), it is unlikely that fielded PV systems would be allowed to reach a saturated loading condition. Low soil mass loadings represent a much more common; albeit difficult to quantify, occurrence. Models appropriate for heavy mass loadings do not agree well with models describing lighter loadings (Boyle et al., 2013). Measurements of light transmission through soiled glass (haze) have been described by Alfaro et al. (2012) as dependent upon the density of the accumulated soil film. Sparse soil films exhibited a non-linear change in haze, making prediction difficult at low mass loadings. Measurements on assembled PV modules would likely be more difficult, as direct transmission measurements are not feasible. Reflectance measurements on module surfaces have been reported (Murphy and Forman, 1979; Murphy, 1980); however, a direct correlation between the amount of soil and reduction in performance was not made.

Task Objectives: In Task 1, we conduct advanced soiling studies to address one of the largest sources of power loss from PV systems. This work falls into two complementary categories: indoor laboratory studies designed to uncover the physical mechanisms of PV performance loss due to soil coverage and outdoor studies of deposited soil composition and accumulation rate at geographically distinct locations. The tandem goals of this Task are to provide improved methods for representing soil loss within PV performance models (thereby improving accuracy and reducing uncertainty) and to provide a useful tool to industry for the scientific study of soiling mechanisms and mitigation strategies.

Task Results and Discussion:

Our indoor, laboratory methodology for conducting fundamental studies on soiling effects are documented in SAND2014-19199, "A Handbook on Artificial Soils for Indoor Photovoltaic Soiling Tests." Natural soiling is a highly variable process and the procedures presented in this handbook were developed specifically to enable repeatable measurements under controlled conditions. A standard, neutral "grime" composition and formulation method was described. Where possible, components were obtained from commercial (and preferably traceable) sources. However, many natural soil components are not available as commercial products, so repeatable synthesis techniques were used to produce consistent test materials.

The standard grime was formulated based on compositional analysis of samples collected from typical soiled surfaces in an urban environment. Common environmental components, primarily sand and soot, were replicated using AZ road dust and a soot blend. Modifications to the base grime were made to incorporate spectrally responsive minerals to emulate natural soils. Blends of Hematite and Goethite, common red and yellow iron oxides found in wide distribution across the US were primarily used as the spectrally responsive components. Blends were formulated on a mass basis but categorized using the Munsell color chart that is commonly used by the USDA for soil color classification. The formulated grime powder blend was then dispersed in acetonitrile using conventional colloidal dispersion techniques. A commercial high velocity low-pressure (30 psi) automotive detailing paint gun was used to apply a uniform coating of the grime to various test coupons.

Subsequent characterization involved several techniques, including gravimetric analysis, various optical methods and quantitative x-ray fluorescence. Gravimetric analysis was performed to quantify the mass of soil on each coupon. The impact of the soil layer to an underlying (if hypothetical) PV absorber was quantified using UV-Vis spectroscopy, Quantum Efficiency (QE) and IV curves obtained using a 1-sun AAA light source. For QE and IV measurements, a bare mc-Si cell was used as a detector. UV-Vis and QE measurements provided quantitative measurements of the impact of soil on the spectrum of transmitted light, while IV measurements provided a direct measurement of the impact to the electrical performance. Using the appropriate integration techniques, all three methods were shown to be equivalent in terms of characterizing transmission loss as a function of soil mass. Significantly, IV scans demonstrated that soil coatings have no effect on open circuit voltage, but impact short circuit current directly.

Examination of soil composition revealed a few important trends. First, soils containing primarily soot and sand provided a neutral response with no impact to the spectrum of the transmitted light. Secondly, these formulations were highly susceptible to the soot content. On a mass basis, soot was found to have a 10-fold impact on transmission loss vs sand. This finding is particularly relevant to PV systems deployed in areas with significant pollution from combustion. PV systems near industrial areas or airports may be more susceptible to soiling losses than systems located in rural or agricultural areas.

Likewise, examination of soils containing pigment blends was revealing. Yellow Goethite rich soils displayed greater spectral sensitivity overall, absorbing considerably in the UV to green wavelengths (~300 – 500nm), but very little above ~600nm. In contrast, red hematite rich soils displayed a more neutral absorption. The greatest impact to transmission loss came from an intermediate blend of these two, which displayed a strong peak in the UV to green coupled with high absorption from 500 – 1200 nm.

The techniques described above were used to conduct a feasibility study to evaluate the anti-soiling properties of different glass coatings in collaboration with Diamon Fusion, a glass coating company. These results were not published but were provided to Diamon Fusion through private communication. The artificial soiling methodology was used to apply a simple soil layer to untreated glass coupons and two glass coupons treated with different coatings. The effectiveness of each coating to mitigate the impact of the soil layer and ability to release soil during a cleaning operation was evaluated through light transmission loss measurements. The results of this feasibility study indicated that the two treatments promoted a uniform coating of soil when applied artificially when compared to an untreated glass sample. The uniformity of the soil coating appeared to result in overall lower transmission loss. This was likely due to the uniform coating allowing scattered light to still be transmitted to the underlying PV cell, whereas large islands of soil present on the untreated sample were sufficiently thick to promote reflection of incident light rather than transmission. However, under a simple rinse, only one of the treatments appeared to promote sufficient release of the applied soil such that transmission loss was fully recovered. The other treatment appeared to not promote sufficient release to impact transmission loss, while transmission loss of the untreated sample actually appeared to worsen. Mechanical wiping was sufficient to restore transmission for all three samples. While not directly correlated to outdoor exposure tests, these results highlight the potential value of using the indoor methodology to characterize and optimize soil mitigation strategies.

Our laboratory work was complemented by three types of soiling stations installed at multiple sites across the US (including multiple Regional Test Center locations) to confirm the influence of soil composition on performance and correlate to laboratory studies. Two stations, built and deployed by CU-Boulder, include ambient air sampling equipment and glass collection plates to provide better understanding the interrelationship between suspended particulate matter, natural soil deposition rates and composition. The third type of station, built and deployed by ASU, monitors the impact of soil accumulation on the electrical performance of calibrated PV reference devices.

Site	Atmospheric	Electrical
NM RTC (Sandia)	x	x
CO RTC (NREL)	x	x
FL RTC (FSEC)	x	x
VT RTC (IBM)		x
Arizona State University		x
Commerce City, CO	x	
Boulder, CO	x	

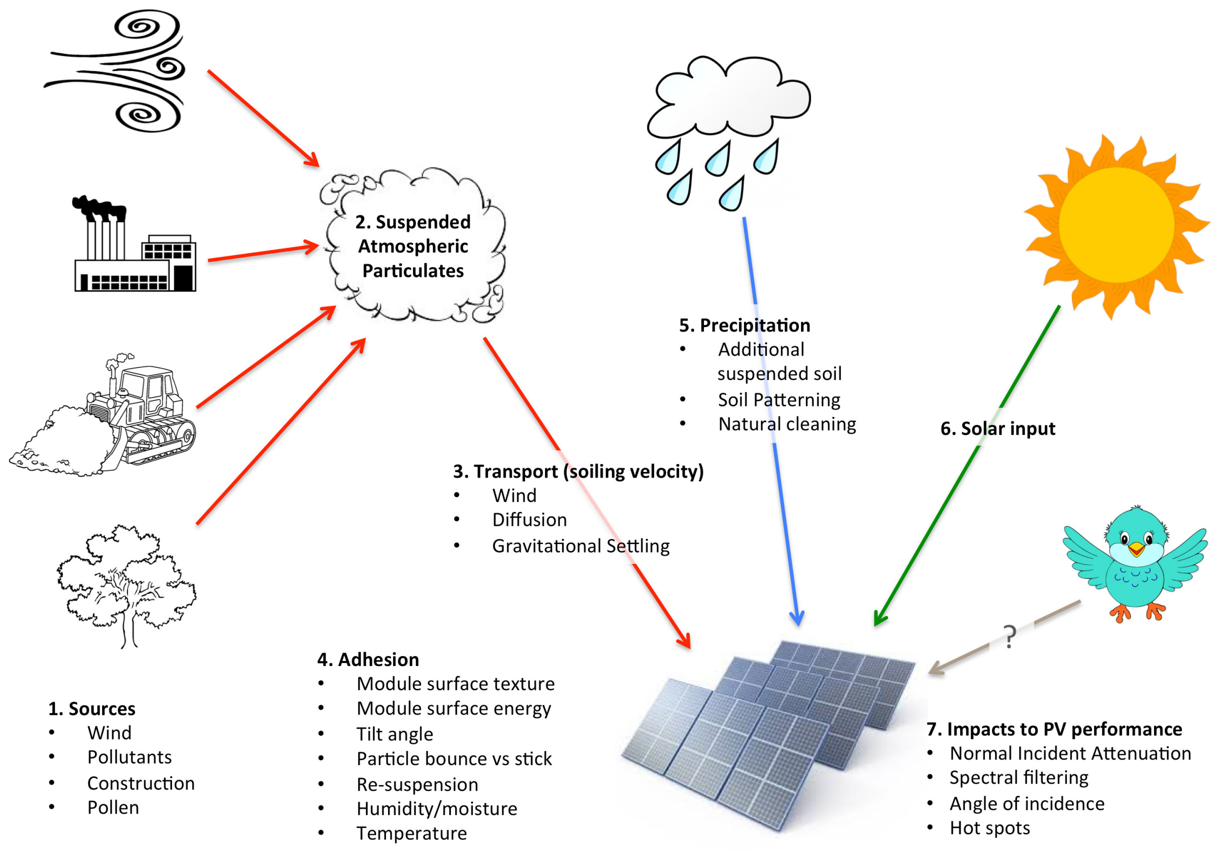
Atmospheric sampling stations sample airborne particulates directly. Airborne particles smaller than 2.5 μm typically originate from atmospheric reactions or from combustion and consist of carbonaceous material, sulfate and nitrate while particles larger than 2.5 μm originate from abrasion processes and are thought to be more similar to local soils and pollens. The sampling stations for determining total suspended particulates (TSP) consist of Hi-Vol TSP filter samplers such as the Tisch environmental TE-5000 set to pull 1000 L/min of air through an 8 x 10 inch quartz fiber filter. The filter is weighed before and after deployment to estimate the concentration of total suspended particulates in the air. Additionally, custom-built dichotomous particle samplers that collect air particulate matter above and below 2.5 μm in separate channels are deployed at select locations.

Stations for collecting naturally deposited soil consist of a mounting plane for deploying stationary glass coupons at tilt angles of 0° and 40°. Each mounting plane is a large acrylic sheet designed to eliminate edge effects. Stations are sheltered to limit the degree of natural cleaning due to precipitation and preserve the deposited soil. Glass coupons are similar to the cover plates used on PV panels and are weighed before and after being deployed in a temperature and relative humidity controlled chamber on an analytical balance with a 0.00001-g accuracy to determine the mass of accumulated particulates. Following gravimetric analysis, samples are characterized for transmission as described above.

Electrical performance loss stations consist of custom fabricated sensors employing matched half-cells cut from a single monocrystalline silicon cell and assembled in a package that resembles a conventional split reference cell. Each half-cell sensor is fitted with a precision low temperature coefficient current shunt between the positive and negative terminals of the cell. The I_{sc} of each half-cell is determined by measuring the voltage drop across the current shunt. The temperature of each half-cell is measured at the center of the backsheet using a T-type thermocouple. One half of the sensor is cleaned periodically while the other is allowed to soil naturally. Performance loss is determined by comparing I_{sc} between the two halves. The use of matched half-cells minimizes I_{sc} mismatch between each sensor, while packaging in the same laminate ensures co-planarity which automatically eliminates the tilt angle and azimuth angle misalignment artifacts often observed in the individual sensor- or module-based soiling stations. To quantify the effects of module tilt angle on soil accumulation rate and of angle of incidence on soiling density, a total of 10 split sensors are deployed at tilt angles of 0–45°. A data logger records each signal once a minute.

Results from all three stations are forthcoming, as graduate students are conducting the research on these. However, a few observations can be made. First, an analysis of total suspended particulate concentrations against mass accumulation on glass plates revealed a generally linear trend; higher particulate concentrations lead to higher accumulations. Second, both airborne concentration and mass accumulation were generally higher at one site in Commerce City, CO. This area is generally known to be a heavily industrial area. Second, preliminary transmission loss measurements across all sites produced a linear response against mass accumulation. While there is certainly scatter in the data, this observation may support a claim that the composition of accumulated soil is rather simple without a significant spectral component. This claim cannot be verified without compositional analysis of the collected soils. However, if it proves to be true could have significant implications for developing soil mitigation strategies and for performance modeling.

Lastly, our research has enabled us to present a high-level view of the processes that lead to the suspension of particulates in the atmosphere and their ultimate impact on PV system performance.



Task 2: Improved Modeling of Angle of Incidence Losses (FY13 and FY15)

Background: The majority of flat plate PV modules are mounted in a fixed orientation such that the incident irradiance is rarely directly normal to the surface of the module. Two energy loss mechanisms arise due to the Angle of Incidence (AOI) effects on direct normal irradiance (DNI). The first, cosine loss due to the projection of the direct irradiance onto the tilted module surface, is easily accounted for given sun position and module orientation. The second, reflection of the direct incident irradiance, becomes more pronounced at incidence angles greater than ~ 50°, and is affected by the optical properties of the module. Accurate performance models for PV system energy prediction rely on being able to effectively represent the reflective loss component due to angle of incidence.

King [1] presented a method for experimentally measuring the AOI response of a module outdoors using a two-axis tracker to articulate the module to achieve a range of AOI. More recent work [2] has built upon and validated this basic methodology. A key outcome of the more recent study is the recommendation that AOI need not be measured for standard flat plate modules with uncoated glass [3]. However, factors such as texture, anti-reflective coatings, soiling, glass composition or the use of a polymeric cover, may change the scattering and reflective properties of the glass-air interface and the AOI response of a PV module. In these cases, use of the “standard” loss function [2 - 4] is not appropriate. In particular, as soil builds up on the module over time, the effect may become more pronounced.

Task Objectives: The angle between the incident light from the sun and a PV module dictates the fraction of the direct irradiance that is reflected or scattered and the fraction that is transmitted and available for conversion into electrical energy. Accumulation of soil over time changes the scattering and reflective properties of the module and may change the Angle of Incidence (AOI) response of a PV module. In this task, we will use artificial soiling methods to systematically understand the impact of soil accumulation on AOI response.

Task Results and Discussion: This task was conducted in only two of the three years of the project period. With only a few exceptions, angle of incidence testing of PV modules is performed outdoors under real-world conditions. Measurements can be contaminated by albedo or stray reflections from both the near and far horizon. Measurements are most commonly made on two-axis trackers designed to track the sun to maximize power production; these often lack the range of motion necessary to adequately characterize AOI response. Further, these trackers often lack the sophisticated controls required to steer the tracker off axis to prescribed incident angles or the ability to continue to track the sun in those off-axis configurations.

In the first year of this project (FY13), we invested in a significant effort to develop a new tracker control system to address the limitations associated with conventional outdoor AOI testing. Our base platform was a repurposed two-axis azimuth-elevation tracker originally developed as a heliostat for concentrating solar power (CSP) towers. This type of tracker has a more flexible drive system than more affordable trackers based on linear actuators and thus is able to achieve a significantly greater range of motion. The control system was based on a National Instruments CompactRIO system, running a real-time version of LabView. The control software leverages the Sun Position Algorithm (SPA) developed at NREL to provide a highly accurate sun position at all times.

The core algorithm of the control system is described in SAND2014-3242, “Sun-Relative Pointing for Dual-Axis Solar Trackers Employing Azimuth and Elevation Rotations.” Here, we describe a steering algorithm to accurately point the tracker away from the sun such that a vector projection of the sun direct normal beam onto the tracker face falls along a desired path relative to the tracker face. This algorithm produces the appropriate azimuth and elevation angles for a dual axis tracker when given the sun position, desired angle of incidence, and the desired projection of the sun direct normal beam onto the tracker face. We further defined a new term, angle of incidence direction, defined by the projection onto the tracker face of the vector from the sun to the tracker. We quantify this angle over the interval (0, 360) in degrees counterclockwise from the line between the module’s center and the module’s “top.”

This control system enabled several advancements in PV characterization, described in the final reports associated with other LPDP projects conducted by Sandia between FY14 and FY15. First, it enabled a new method to measure AOI response of flat plate modules, described in “Recent Advancements in Outdoor Measurement Techniques for Angle of Incidence Effects,” and reported in the final report for 25799 – Emerging Technologies. This approach for measuring angle of incidence response has become Sandia’s preferred method. Second, it enabled the development of a new angle of incidence model for low-x CPV trackers. This model was validated through extensive collaboration with SunPower on the development of their C7 product. Lastly, it enabled the development of a method for mapping the optical response of High-X CPV systems, described in “Mapping HCPV Module or System Response to Solar Incident Angle,” and reported in the final report for 25798 – Increasing Prediction Accuracy.

In FY15, we returned to the question of the impact of soil accumulation. As described in “Pattern Effects of Soil on Photovoltaic Modules,” we leveraged the laboratory soiling methods developed under Task 1 of this project to conduct systematic studies of the impact of soil accumulation on AOI response. Here, we used a PV test coupon identical to those used for the electrical performance loss stations. One side was coated with a specific mass loading of soil while the other remained clean, as a control. Multiple test coupons were prepared with varying levels of soil and characterized outdoors on the two-axis tracker. It was observed that soiling had an immediate impact on the angle of incidence response of the test coupons, causing losses in short circuit current under off-axis conditions that were greater than would be expected based on either direct normal or transmission measurements. For light soil loading (~ 0.25 g/m^2), the deviation was on the order of a few percent up to an AOI of around 40-50°, after which the deviation increased to ~10%. However, at higher mass loadings (> 2.5 g/m^2), the effect becauem much more pronounced. Significant deviation was observed at small AOI, around 10-20° and the deviation was up to ~20% at 50°. Response dropped to 0 at 80°, meaning that under these conditions, all light was being scattered away from the module and output had dropped to 0 watts.

The implications of these observations are significant, particularly in the case of commercial, rooftop PV systems. Such systems are typically deployed at shallow angles of 10°. At these shallow angles, the sun will only be directly overhead for systems installed at low latitudes and then only at the summer solstice. For all other installations, the system will always be at a non-optimal high incident angle configuration. Further, we have previously observed that soil accumulation is much more rapid at shallow tilt angles than at the higher tilt angles that are more common for ground mount systems. Exacerbated by sporadic (or nonexistent) cleaning schedules, these systems may be doubly susceptible to losses due to soil accumulation.

Task 3: Improved Modeling of Solar Spectrum Effects (FY13 and FY14)

Background: The power output of all PV devices is sensitive to the spectrum of the incident solar light, which can vary considerably with changes in atmospheric conditions. Current spectral models generally produce prediction errors for short circuit current (I_{sc}) of up to 3% uncertainty for Si-based technologies, and as high as 5% for thin-film technologies, over a 90% confidence interval. Commonly used spectral models are either overly simplistic and do not have enough inputs to represent the effects of fluctuating spectrum or overly complex, requiring sophisticated inputs and significant post-processing. State-of-the-art spectrophotometers for measuring actual incident solar spectrum that are rated for continuous outdoor use are expensive (~$80,000) and complex to use. This normally relegates these measurements to research activities and minimizes the value of correcting performance models to account for it.

Task Objectives: The Sandia team will deliver an improved method of accounting for the effects of solar spectrum on PV performance. This method will utilize a combination of an improved spectral model with one or more low-cost sensors as inputs to the model. The goals for this effort are to simultaneously reduce the uncertainty due to changes in spectral content by 50% and reduce the cost of instrumentation required to achieve this accuracy from ~$80,000 to less than $1000.

Task Results and Discussion: This task was completed at the end of FY14. A brief summary and update is included here for completeness.

Accomplishments for this Task included performing an extensive review of published spectral performance factors, developing a new spectral performance factor that accounts for precipitable water (ACSF), studying the effects of daily and seasonal spectral variations on the PV module performance, and finally developing a prototype sensor that will measure the solar spectrum at several discrete wavebands and use the data to predict the solar spectrum and the PV module short-circuit current

Development of the Atmospheric Component Spectral Factor (ACSF) is described in “A Review of Spectral Performance Factors and Derates Phenomena.” This approach, which heavily relies on calculations using MODTRAN5, ultimately proved to be an unwieldy replacement for the much simpler (and more common) use of air mas to represent spectral effects. Consequently, Sandia has abandoned this approach. Instead, as detailed in the final report for 25799 – Emerging Technologies, we have been exploring systematic variations in air mass that occur seasonally and geographically. As reported in the final report for 257978 – Increasing Prediction Accuracy, two new spectral models were proposed at the 2015 PV Performance Modeling Workshop. These spectral models are under evaluation at Sandia and will be included in an upcoming release of the PV_LIB Toolbox.

A survey of spectrometers available in 2014 revealed a wide range both in terms of cost and wavelength. In general, lower cost solutions were not ruggedized for outdoor use and covered a more restrictive range of wavelengths. Consequently, we developed a lost cost spectrometer based on the measurement of discrete spectral bands corresponding to common absorption bands known to vary with concentration of specific atmospheric components (e.g. water vapor, ozone, various aerosols and particulates). The measured data from these sensors may then be applied to an atmospheric spectral model such as MODTRAN5 or SMARTS to recreate the incident solar spectrum. The description of this spectrometer was submitted to Sandia Legal as a Technical Advance and as of Fall 2015 is still awaiting a decision as to whether or not a patent application will be pursued.

Task 4: Methods to Quantify and Predict the Impact of Mismatch Losses on PV Array Performance

Background: Photovoltaic arrays are typically constructed by connecting a large number of series-connected strings of individual modules in parallel. Variation in the electrical performance of the modules comprising a string reduces the power produced by the string, typically due to current mismatch between modules. At the array level, mismatch in voltage between parallel-connected strings will also lead to a reduction in power production. These electrical losses are often termed mismatch loss.

Current PV performance models [King], [PVsyst], [SAM] represent the effect of module mismatch on the array performance by a simple percent reduction in predicted power. Likewise, all major performance models treat the array as being constructed of identical modules. Both PVsyst and SAM implement a derate factor to account for mismatch between modules – “module quality loss factor” (PVsyst) and “nameplate loss factor” (SAM). Both include a separate array mismatch loss factor. PVsyst includes a tool to estimate the array mismatch loss factor from statistics for module performance parameters (e.g., Voc, Isc). Beyond this tool there exists little basis for setting these derate factors except for intuition. As a consequence, additional uncertainty is ascribed to predicted system performance arising from these derate factors.

The need for these simplistic percent derate factors arises from the fact that these PV performance models are typically applied using a set of coefficients determined for a single, representative module rather than from a statistical sample of modules. While some manufacturers may test larger samples of modules, IEC 61215/61646 only requires that a single module be tested for electrical performance. Even when multiple modules are characterized, methods are not documented and validated to determine model coefficients that will accurate predict performance of a string of such modules. Using coefficients from only a single module is likely to introduce bias errors into predictions of system power.

At a recent workshop hosted by Sandia and attended by representatives from the PV modeling, manufacturing, finance and system integrator communities, uncertainty surrounding mismatch losses was identified as a significant gap in current performance models (Cameron 2011). Field measurements of mismatch losses, however, have shown the effect to be relatively small even for modules with significantly different current-voltage characteristics [MacAlpine]. Modeling studies have also shown that the effect of mismatch on power production is relatively small [Helioscope] and also is small relative to other uncertainties in performance models [Hansen].

Task Objectives: All major PV performance models treat the array as being constructed of identical modules while applying a scalar derate factor to account for module variability and mismatch. Currently, methods do not exist to determine average performance coefficients from testing of multiple module samples. In this task, we will develop and validate methods to estimate string-level performance model coefficients from the characterization of a sample of individual modules.

Task Results and Discussion: The results of this Task are described in SAND2015-xxxx, “Predictive Model for Photovoltaic String Level Mismatch Based on Individual

Module Measurements" (currently unpublished). Here, we evaluated three different methods to determine coefficients for the Sandia Array Performance Model (SAPM) [King] from individual module testing in order to best represent the performance of a string of similar modules. The evaluation included individual thermal and electrical characterization of ten Suntech STP0802-12 modules as well as characterization of two strings of five modules each. Our evaluation followed a three-step process. First, each module was individually characterized outdoors on a two-axis tracker to determine module-level coefficients for the SAPM. The module-level coefficients were then aggregated into string-level coefficients using two different methods. Next, the modules were configured as two strings of five modules each, characterized on the two-axis tracker and string-level coefficients for the SAPM were developed. Finally, string level predictions from each of these three methods were compared to out-of-sample measured data from the string-level tracker measurements to determine the effectiveness of each.

The three methods under investigation were termed the Average Module Method, the Random Module Method and the Average String Method. The Average Module Method is a physically informed method that estimates string-level coefficients and parameters by "averaging" the corresponding values for individual modules. This description is an over-simplification, because many of the coefficients in the SAPM cannot be combined using an arithmetic average. The Random Module Method simply selects (at random) one of the characterized modules as representative of all modules in the string and models the string by scaling the module-level coefficients for the selected module. The Average String Method requires electrical characterization of the actual string of modules, from which string-level coefficients and parameters for the SAPM can be determined using the same methods as are used for module data.

The coefficients developed by each of the three methods were then used with the SAPM to predict power for out-of-sample data for each of the five strings of modules. The model was provided with actual weather inputs measured during the tests, such as outside air temperature, solar irradiance, and average module temperature. The three methods performed similarly. Each of them was able to represent system behavior very well and produce an R^2 value close to 1.0, although there were slight variations in the linear correlation tests. Not surprisingly, the method with the best results was the Average String Method. The next best approach was the Average Module Method followed by the Random Module Method.

While most representative of a string, the Average String Method is currently not practical for most test labs (including Sandia). This method requires that a realistic sized string be mounted on the test plane of a two-axis tracker. It further requires adequately sized electronic loads and IV sweep hardware for characterizing the string. We were able to test strings of five modules in this case because of the small size of the Suntech modules (80W each). The combined power and voltage of these rather short strings was just at the limit of our measurement hardware (400W and 110V Voc). In contrast, a similarly sized string of common 60-cell modules could be 1350W and 200V Voc. A truly representative string of 10-12 modules would obviously require even larger loads and high voltage sweep capability. While such loads exist for field commissioning of PV systems, they typically are not considered accurate enough for research or certification purposes. The high voltage of such realistic strings also presents a significant safety hazard to lab personnel that is not common in a module-testing environment.

In contrast, the Average Module Method is much more practical. Individual modules can either be tested simultaneously on a two-axis tracker or serially. Accurate, research grade IV sweep hardware sized to test individual modules is commonplace at module test facilities. Low DC voltages (<100V) are generally safe to work with. As such, we recommend use of the Average Module Method in cases where sufficient test data is available.

Accomplishments:

Peer-Reviewed Journal Articles:

K. M. Armijo, R. K. Harrison, B. H. King and J. B. Martin, "Spectral derates phenomena of atmospheric components on multi-junction CPV technologies", in AIP Journal, vol. 1616, pp. 264-271, 2014

K.M. Armijo and J. Yellowhair, “A Review of Spectral Performance Factors and Derates Phenomena,” Progress in Photovoltaics, 2014, Submitted

L. Boyle, P. Burton, H. Flinchpaugh, V. Danner, C. Robinson, K. Blackwell, B. King and M. Hannigan, “Spatial Variability of Soiling of Photovoltaic Cover Plates: Results from Colorado, Florida and New Mexico,” in preparation

P. D. Burton and B. H. King, "Application and Characterization of an Artificial Grime for Photovoltaic Soiling Studies," IEEE Journal of Photovoltaics, vol. 4, pp. 299-303, 2014

P. D. Burton and B. H. King, "Spectral Sensitivity of Simulated Photovoltaic Module Soiling for a Variety of Synthesized Soil Types," IEEE Journal of Photovoltaics, vol. 4, pp. 890-898, 2014

P.D. Burton, B.H. King, D. Riley, “Predicting the spectral effect of soils on high concentrating photovoltaic systems,” *Solar Energy*, vol. 112, pp. 469–474, 2015

P. D. Burton, L. Boyle, J. J. M. Griego, and B. H. King, "Quantification of a Minimum Detectable Soiling Level to Affect Photovoltaic Devices by Natural and Simulated Soils," *Photovoltaics, IEEE Journal of*, vol. 5, pp. 1143-1149, 2015

P. D. Burton, A. Hendrickson, S. S. Ulibarri and B. H. King, Pattern Effects of Soil on Photovoltaic Surfaces, submitted to Journal of Photovoltaics

D. Riley, C.W. Hansen, “Sun-Relative Pointing For Dual-Axis Solar Trackers Employing Azimuth and Elevation Rotations,” *ASME Journal of Solar Energy Engineering,* vol. 137, 2015

Conference Publications:

K.M. Armijo, R.K. Harrison, B.H. King, B.H. and J.B. Martin, “Spectral derates phenomena of atmospheric components on multi-junction CPV modules”, 10th International Conference on Concentrator Photovoltaic Systems, Albuquerque, NM, 2014

L. Boyle, P. Burton, H. Flinchpaugh, V. Danner, C. Robinson, K. Blackwell, B. King and M. Hannigan, Initial Results of a Five Site Study Comparing Spatial Variability of Soiling and Ambient Particulate Concentrations, 42nd IEEE Photovoltaic Specialists Conference, New Orleans, LA, 2015

P. D. Burton and B. H. King, "Artificial soiling of photovoltaic module surfaces using traceable soil components," 39th IEEE Photovoltaic Specialists Conference, Tampa, FL, 2013

P. D. Burton and B. H. King, "Determination of a Minimum Soiling Level to Affect

Photovoltaic Devices," 40th IEEE Photovoltaic Specialists Conference, Denver, CO, 2014

P. D. Burton, A. Hendrickson and B. H. King, Macro- and Microscale Particle Size Effects of Soil on Photovoltaic Surfaces, 42nd IEEE Photovoltaic Specialists Conference, New Orleans, LA, 2015

B. King, G. TamizhMani, S. Tatapudi, V. Rajasekar and S. Boppana, Regional Soiling Stations for PV: Design, Calibration and Installation, 42nd IEEE Photovoltaic Specialists Conference, New Orleans, LA, 2015

Sandia Technical Publications:

Patrick D. Burton and Bruce H. King, "A Handbook on Artificial Soils for Indoor Photovoltaic Soiling Tests," SAND2014-19199, Sandia National Laboratories, Albuquerque, NM, 2014

D. M. Riley and C. W. Hansen, "Sun-Relative Pointing for Dual-Axis Solar Trackers Employing Azimuth and Elevation Rotations," SAND2014-3242, Sandia National Laboratories, Albuquerque, NM, 2014

C. Birk Jones, Clifford W. Hansen and Bruce H. King, "Modeling of Photovoltaic Strings Based on Individual Module Measurements," SAND2015-xxxx, Sandia National Laboratories, Albuquerque, NM, (in preparation)

Patent Applications:

"Low Cost Trackerless Spectral Sensor," Kenneth Armijo, et. al. Technical Advance filed with Sandia Legal for consideration for a Patent Application.

Path Forward:

Formulation and Validation of Predictive Soiling models

- Draw from existing expertise in environmental sciences
- Tie deposition modeling to existing ubiquitous data sources
  - EPA Air Quality monitoring stations
  - Satellite data - suspended aerosols

Relaunch low-cost spectral sensor work terminated at the end of FY14

- Spectral irradiance effects have been identified as a significant source of uncertainty in PV performance models with significant international

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